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ABSTRACT

The search for new energy resources as alternatives to fossil fuels have generated new interest in the heat of the earth itself. New geothermal areas with a variety of characteristics are being explored, as are new ways of extracting work from naturally heated steam and hot water. Some of this effort is discussed in this three-part module. Five types of geothermal resources and their development and utilization are reviewed in the first section. Geothermal energy and related principles are discussed in the second section. These include: force, work, energy, power; absolute temperature and pressure; heat engines, carnot engine; enthalpy; and availability and maximum work. Geothermal energy utilization is discussed in the third section, focusing on electricity generated from and non-electrical applications of geothermal energy. Also included in the module are study questions (with answers), a list of references, and, in appendices, measurement tables and tables of properties of saturated steam and saturated water (temperature, pressure) and properties of superheated steam and compressed water (temperature and pressure). The module contains the equivalent of 1-week's material and is suitable for use in introductory college physics courses and in advanced high school physics programs. (JN)

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GEOTHERMAL ENERGY:

RESOURCE AND UTILIZATION

A Teaching Module Written for

The American Association of Physics Teachers

by

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The MITRE Corporation
McLean, Virginia 22102
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March 1979

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The search for new energy resources as alternatives to fossil fuels have generated new interest in the heat of the earth itself. New geothermal areas with a variety of characteristics are being explored, as are new ways of extracting work from naturally heated steam and hot water. Some of this effort is reviewed in this account.

1.0 CURRENT STATUS OF GEOTHERMAL ENERGY

1.1 Geothermal Energy Resources

Geothermal energy can be defined as the thermal energy (heat) stored below the earth surface. Geothermal energy resources may be classified into five types:

* Hydrothermal Convective Resources: - Systems containing relatively high temperature water at shallow depth. The water often contains impurities, particularly sodium ion (Na^+) and Chloride ion (Cl^-), and may be called brine. There are two types of hydrothermal resources:

  (i) Vapor-dominated hydrothermal resources: these resources produce dry steam in the superheated state (the state at which steam temperature is higher than the boiling point at a given pressure). Steam temperature is generally greater than 300°F.

  (ii) Liquid-dominated hydrothermal resources: These resources produce mixtures of steam and water. The mixtures are usually called wet-steam. Since steam and brine are in contact, they can be assumed to be in equilibrium and therefore are referred to as saturated steam and saturated water. The temperatures of these resources range from below 200°F (e.g. hot springs water) to greater than 600°F.

* Geopressured Resources: - Geopressured resources are usually found at greater depths than hydrothermal resources. They contain large amounts of pressurized water with high concentrations of methane. Geopressured resources found so far have a temperature range from 250° to 450°F and a methane concentration range from 30 to 50 standard cubic feet (measured at 60°F and 1 atmosphere pressure) per barrel.

* Hot Dry Rocks: - Systems that contain very hot, non-molten rock formations. Rock temperatures can reach 1200°F. The energy can be brought to the surface by injecting water into the rock formations to absorb the heat, and then allowing the hot fluid (steam or mixtures of steam and water) to escape to the surface for utilization. The method thus involves an injection well and a production well and is often called the "two-hole" method.

* Normal Gradients: - These are basically the temperature gradients in the earth's crust formations which exist because of the heat transfer from areas heated by a variety of sources, such as radioactive decay of matter. The energy available in these resources is relatively limited.

* Magma Resources: - These resources contain molten rock at temperatures exceeding 1200°F. The energy contained in these resources is large, but because of the great depths and difficulties in extracting the energy, utilization of magma resources is still in the distant future.

1.2 Development and Utilization

Natural geothermal water has been used in isolated areas for various heating purposes for many years. But only in the last 30 years has geothermal energy been utilized to meet a significant fraction of the energy requirements of any country. This modern trend can be traced back to the beginning of the century, when the first attempt to use natural steam to heat a boiler and produce pure steam for a reciprocating steam engine was made in Larderello, Italy. In 1904 the first electric power generated from geothermal energy was demonstrated and 8 years later the first commercial geothermal-electric unit (0.25 Mega-Watts) was installed in the same area.

Currently, only hydrothermal convective resources are developed and only some of them are utilized. Not all of the areas having active geothermal energy programs shown in Figure 1 are currently producing. Uses of geothermal energy can be conveniently classified into two categories. One is the use for electricity generation and the other includes all non-electric uses.

FIG. 1: World map showing some of the main centers of geothermal investigation and development. (Reproduced from reference 4)

Electricity Generation

In 1960, Italy, New Zealand and the U.S.A. produced the entire world total of 386.4 Megawatts of geothermal electrical power. In 1978, the world geothermal electric capacity included ten countries and reached a total of 1466.6 Megawatts as shown in Table 1. Also shown in Table 1, an additional 1817 Megawatts are planned to be on line by 1982. (1)

Non-Electrical Applications

As mentioned before, non-electrical applications of geothermal energy existed long before the installation of the first geothermal power plant in Larderello, Italy, but information on these applications is rather sketchy. The best data available are perhaps those reported in reference 3 and condensed in Table 2.

TABLE 1

TOTAL INSTALLED CAPACITY OF GEOTHERMAL

POWER PLANTS BY 1978

(In Megawatts)

COUNTRY	CURRENT	PLANNED *
El Savador	60.0	35
Iceland	33.0	30
Italy	417.6	-
Japan	166.0	100
Mexico	75.0	105
New Zealand	202.6	150
Philippines	4.2	605
Turkey	0.5	-
U.S.S.R.	5.7	58
U.S.A.	502.0	734
TOTAL	1466.6	1817

NOTE: Data compiled from Reference 2.

* To be on line by 1982

TABLE 2

TOTAL POWER IN NON-ELECTRICAL

APPLICATIONS OF GEOTHERMAL ENERGY BY 1975

(In Megawatts)

COUNTRY	1	2	3	Total
France	4	-	-	4
Hungary	-	320	-	320
Iceland	186	39	39	264
Italy	-	5	19	24
Japan	8	25	-	33
New Zealand	250	-	125	375
Philippines	-	-	5	5
U.S.S.R.	114	5011	-	5125
U.S.A.	15	1	-	16
TOTAL	577	5401	188	6166

1: Residential and Commercial Space Heating

2: Agricultural Applications

3: Industrial Applications

NOTE: Data condensed from reference 3.

As shown in Table 2, 6166 Megawatts of non-electrical power were reportedly extracted from the geothermal fluid by 1975. This figure is about four times the 1978 electrical capacity. But it must be noted that the energy conversion efficiency is much higher in non-electrical applications than in electricity generation. One Megawatt of power available in the geothermal fluid can produce heat at the rate of about 0.85, but can produce only about 0.10 Megawatts of electrical power.

Non-electrical applications of geothermal energy include residential and commercial space heating during cold weather; agricultural applications such as green house heating, animal husbandry, eel and salmon breeding; and industrial applications such as process steam for pulp and paper industry, and recovery of minerals from the geothermal fluid. Up to now, it appears that the potential of non-electrical applications of geothermal energy has not been fully realized. Except for those in Iceland and New Zealand, non-electrical applications have been carried out on a "do-it-yourself" basis and have been heavily dependent on the ingenuity and needs of individuals who happen to have access to the resource.

QUESTIONS

1.1 Five types of geothermal energy resources have been identified. What are they?

1.2 Briefly describe the types of geothermal energy resources that are currently utilized.

1.3 If 10% and 85% are assumed to be the efficiencies for electricity generation and non-electrical production, respectively, from geothermal energy, what is the fraction of the world total geothermal energy currently being used in non-electrical applications? (Use the total productions shown in Tables 1 and 2.)

1.4 The U.S.A. is presently producing 502 Megawatts of electrical power from its geothermal resources at the Geysers, California. The fluid from the Geysers is dry steam which possesses such properties that 1 Megawatt of thermal power available in it can be converted to 0.17 Megawatt of electrical power. If 1 pound of this steam contains 1100 BTU of available heat, how much steam is being extracted from the ground per hour?

1 Megawatt = 3.145 Million BTU/hr.

2.0 GEOTHERMAL ENERGY RELATED PRINCIPLES

Geothermal fluid extracted from one area is usually different from the fluid extracted from another area. The energy available in the fluid varies in both quality and quantity, depending on the location. These variations are, unlike those for oil and natural gas, quite large. For this reason, geothermal fluid is said to be very site-specific.

The site-specific nature of the geothermal fluid gives rise to questions as to how we determine the quantity and quality of the useful energy in the fluid and what variables or properties we use to do so. To answer these questions, a number of physics definitions and principles related to the utilization of geothermal energy are reviewed here. The principles are fundamental and can be found in physics and engineering text books.

2.1 Force, Work, Energy, Power

* Force, according to Newton, is the product of mass and acceleration:

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$F = M \times A \qquad (1)$$

$$\text{Unit: Newton} = \text{Kg} \times \text{m/s}^2$$

* Work is energy utilized as a force acts through a certain distance:

$$\text{Work (or mechanical energy)} = \text{Force} \times \text{Distance}$$

$$E = F \times d \qquad (2)$$

$$\text{Unit: Joule} = \text{Newton} \times \text{m}$$

* Power. The rate of doing work or expending energy per unit time is called Power:

$$\text{Power} = \text{Work (or Energy)/Time}$$

$$P = E/t$$

$$= F \times d/t \text{ for mechanical energy} \qquad (3)$$

$$\text{Unit: Watt} = \text{Joule/s}$$

Equation 3 can be rearranged as follows:

$$Pt = E \qquad (4)$$

Equation 4 indicates that the unit Kilowatt-hour (Kwh) that appears on our home electric bill is an energy unit:

$$1 \text{ Kwh} = 1000 \times 3600 \text{Watt-s} = 360{,}000 \text{ joules}$$

2.2 Absolute Temperature, Absolute Pressure

The temperature of a body is expressed in units called degrees. The familiar Celsius degree (°C) and Fahrenheit degree (°F) are established arbitrarily on the basis of reference points. The Celsius degree is based on the temperature difference between melting ice and boiling water at 1 atmosphere pressure; the scale is set at 0 for melting ice and 100 for boiling water at 1 atmosphere.

Celsius and Fahrenheit scales are relative scales. Their zero points and the magnitudes of each division in the scales are arbitrarily fixed. Hence it is often necessary to use absolute temperature scales which have the zero point at the lowest temperature theoretically possible. The two absolute temperature scales corresponding to the Celsius and Fahrenheit scales are the Kelvin and Rankine scales. The relationship between these scales is that:

$$T\,(^\circ K) = T\,(^\circ C) + 273.16$$

$$T\,(^\circ R) = T\,(^\circ F) + 459.58$$

and

$$T\,(^\circ K) = T\,(^\circ R) \,/\, 1.8$$

Thus the melting ice temperature is 0°C, or 273.16°K, or 32°F, or 491.58°R. It is noted that the temperature differences on the Celsius scale are the same as those on the Kelvin scale, i.e. $\Delta T\,(^\circ K) = \Delta T\,(^\circ C)$. Similarly for the Fahrenheit scale and the Rankine scale.

Pressures, like temperatures, can also be expressed by either absolute or relative scales. The relative pressure is usually called gauge pressure, and is measured relative to the atmospheric pressure - indicated by the barometer reading. The relationship between relative and absolute pressures is that

Absolute pressure = gauge pressure + barometric pressure

2.3 Heat Engines

A heat engine is a device that receives energy in the form of heat from a heat source, converts some of it to useful mechanical energy, and rejects the remainder into a heat sink.

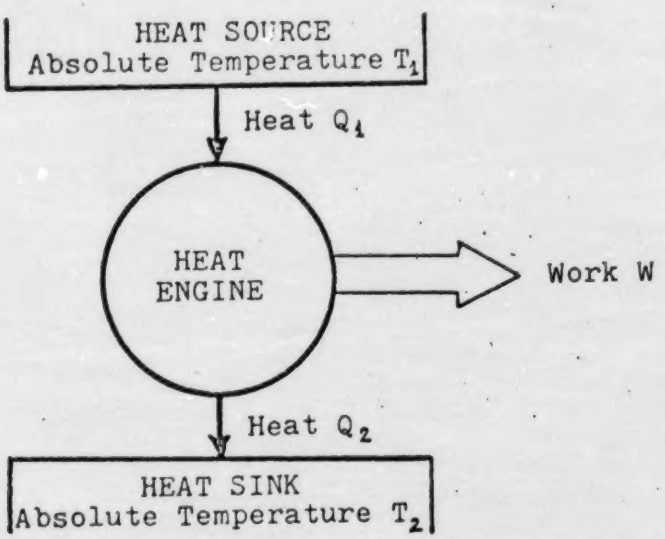


FIG. 2: A Heat Engine receives heat Q_1 at high temperature, converts some of it to work W, and rejects the remainder Q_2 to low temperature sink.

Let Q_1 be the amount of heat the engine receives; Q_2 the amount of heat the engine rejects. The mechanical work output is:

$$W = Q_1 - Q_2 \tag{5}$$

The heat input is Q_1, hence the engine efficiency, by definition, is:

$$\eta_e = \frac{\text{Work output}}{\text{Heat input}} = \frac{Q_1 - Q_2}{Q_1} \tag{6}$$

$$= 1 - \frac{Q_2}{Q_1}$$

2.4 Carnot Engine

The Carnot Engine is a theoretical engine that operates in such a way that

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} ,$$

where T_1 is the absolute temperature of the source, and T_2 the exhaust temperature, that of the heat sink. From equation (6), the Carnot efficiency is equal to:

$$\eta_c = 1 - \frac{T_2}{T_1} \tag{7}$$

If a geothermal fluid having a temperature of 300°F is used to produce mechanical work against a rejection temperature of 100°F, the Carnot (theoretical) efficiency of the operation is:

$$\eta_c = 1 - \frac{100 + 460}{300 + 460}$$

$$= 26.32\%$$

2.5 Enthalpy

The enthalpy H of a substance is defined by:

$$H = U + PV \tag{8}$$

where P is the pressure, and V the volume, both measured quantities. The internal energy, U, of a substance consists of potential and kinetic energy of

the molecules, from a molecular point of view. An increase in enthalpy is equal to the heat absorbed at constant pressure, and is of special importance in engineering because so many thermal processes take place at atmospheric pressure. To calculate the enthalpy per unit mass of a pure substance, the following approximate expression is used:

$$H_2 - H_1 = \int_{T_1}^{T_2} C_p \, dT \qquad (9)$$

where C_p is the heat capacity at constant pressure, defined as the amount of heat (energy) required to raise the substance temperature by 1 degree per unit mass of the substance.

As an example, let C_p be given as:

$$C_p = a + bT$$

where a and b are empirical constants. From equation (9), we have:

$$H_2 - H_1 = a(T_2-T_1) + \frac{1}{2} b (T_2^2 - T_1^2)$$

$$= \left\{ a + \frac{b(T_2+T_1)}{2} \right\} (T_2-T_1)$$

The values of C_p and H are generally available, in a tabulated form, as functions of pressure and temperature (see Appendix B).

In another example, let a geothermal fluid be available at 250°F and have a constant C_p value at 1 Btu/(lb°F).* If the rejection temperature is 100°F and if the fluid is used for heating only, the amount of useful energy (heat) is:

$$H_2 - H_1 = \int_{T_1}^{T_2} C_p \, dt = C_p \Delta T$$

$$= 1.0 \times (250-100) = 150 \text{ Btu/lb of fluid}$$

---

*See unit conversion in Appendix A.

2.6 Availability, Maximum Work

When a fluid is used to deliver mechanical work (not heat), there is a limit on the amount of work it can deliver. This limit is the maximum work W_{max} or the change of "availability," which is calculated by:

$$W_{max} = (H - H_o) - T_o (S - S_o) \qquad (10)$$

where H and S are, respectively, enthalpy and entropy of the fluid. T is the absolute temperature. The subscript o denotes the ambient state or sink.

The entropy of a substance, like enthalpy, has no absolute value; only changes in entropy can be calculated. Often a reference set of conditions is used in computing enthalpy and entropy changes. For water-steam systems, the reference point is liquid water at 32.0°F (0°C). At this point, H and S are zero. The reference point is arbitrary; it does not mean that the enthalpy and entropy are actually zero; but only changes in H and S are of interest here.

Let us use the second example of Section 2.5 and assume that the geothermal fluid is saturated water at 250° F. From the steam-table in Appendix B we have:

H = 218.59 Btu/lb

H_o = 67.999 Btu/lb

T_o = 100 + 460 = 560°F

S = 0.3677 Btu/(lb°F)

S_o = 0.1295 Btu/(lb°F)

W_{max} = (218.59-67.999)-560(0.3677-0.1295)

= 17.20 Btu/lb

The resulting 17.20 Btu/lb, when compared with 150 Btu/lb useful heat obtained in the second example of Section 2.5, clearly show the significant difference between electricity generation where mechanical work is required and non-electrical applications where only heat is required.

2.7 Summary

The objective of this section is to outline the method to determine the following:

* For mechanical work conversion of goethermal energy, what is the maximum work that the geothermal fluid at certain resource can deliver? This maximum work is defined per unit mass of the fluid as:

$$W_{max} = (H - H_o) - T_o (S - S_o)$$

* For the case where only heat is desired, how much energy in the form of heat can be released from the geothermal fluid? The amount of heat released per unit mass of the fluid is calculated by:

$$-(H_1 - H) = -\int_T^{T_1} C_p \, dt$$

To perform the above calculations, enthalpy, entropy, and heat capacity at different states must be known. These variables have been determined as functions of temperature and pressure. Hence, temperature and pressure are the two variables whose values must be provided.

QUESTIONS

2.1 An object having a mass of 10Kg is pulled by a force of 13 Newtons parallel to the frictionless horizontal surface on which it is sliding. What is the resulting acceleration of the object?

2.2 Equation 3 in the text can be rewritten as follows:

$$P = F \times v$$

where v is the velocity. Calculate the rate at which work is done on the object of question 2.1 when it has a velocity of 7.5 m/s.

2.3 Calculate the energy in Kwh (Kilowatt-hour) gained by the object of question 2.1 after it has moved 1250m.

2.4 If the energy gained by the object of question 2.1 has been provided as heat by a 2000 watt-heater, how long was this heater turned on?

2.5 The boiling point of pure water at 1 atmosphere pressure is 100°C. What is the equivalent temperature in (a) Fahrenheit scale? (b) Kelvin scale? and (c) Rankine scale?

2.6 To raise the temperature of 1 gram of water by 1°C, requires an amount of heat called the calorie. How many calories are required to raise 1 gram of water by

(a) 1°K, (b) 1°F, and (c) 1°R?

2.7 A weight of 1/8 pound is resting on a hole of 3/16 in. diameter of pressure cooker lid (see Figure). What is the highest absolute pressure inside the cooker if barometric pressure is 14.6 pounds per square inch?

2.8 Recently, a steam car was designed and built in Australia using a heat source of molten salt (NaCl). The salt was heated by electricity before the driving until it melts at 800°C. During driving the water was pumped through tubes which extend through the molten salt, became steam, delivered mechanical work as it passed through a small high speed turbine, and finally condensed in a radiator. If the ambient temperature is 25°C, what is the Carnot efficiency of this car?

2.9 The heat capacity of a substance is found to obey the following relationship:

$$C_p = a\,(1 + 10^{-2}T + 10^{-4}T^2) \quad \text{BTU/(lb°F)}$$

What is the enthalpy change if the substance is heated to 240°F from 40°F?

2.10 A geothermal well is being considered for heating a hospital. The brine from the well will be used to heat 100 rooms. Each room needs about 10,000 BTU/hr in the coldest day. What is the brine temperature as it leaves the hospital if the brine well head temperature is 190°F and brine flow rate is 40,000 lb/hr? Is the process feasible?

2.11 What is the maximum work that, theoretically, can be delivered by the geothermal fluid in question 2.10 if the ambient temperature is 40°F? (Assume that the fluid is saturated water at well head and rejection point).

2.12 Geothermal fluid is available at 250°F. What is the maximum work that, theoretically, can be delivered by this fluid if the ambient temperature is 80°F and:

(a) The fluid is saturated steam at well head and saturated water at rejection point?

(b) The fluid is saturated water at both well head and rejection point?

2.13 Steam is available at 1000°F, 1000 psia. What is the maximum work available for this steam if it becomes saturated water at rejection point of 100°F?

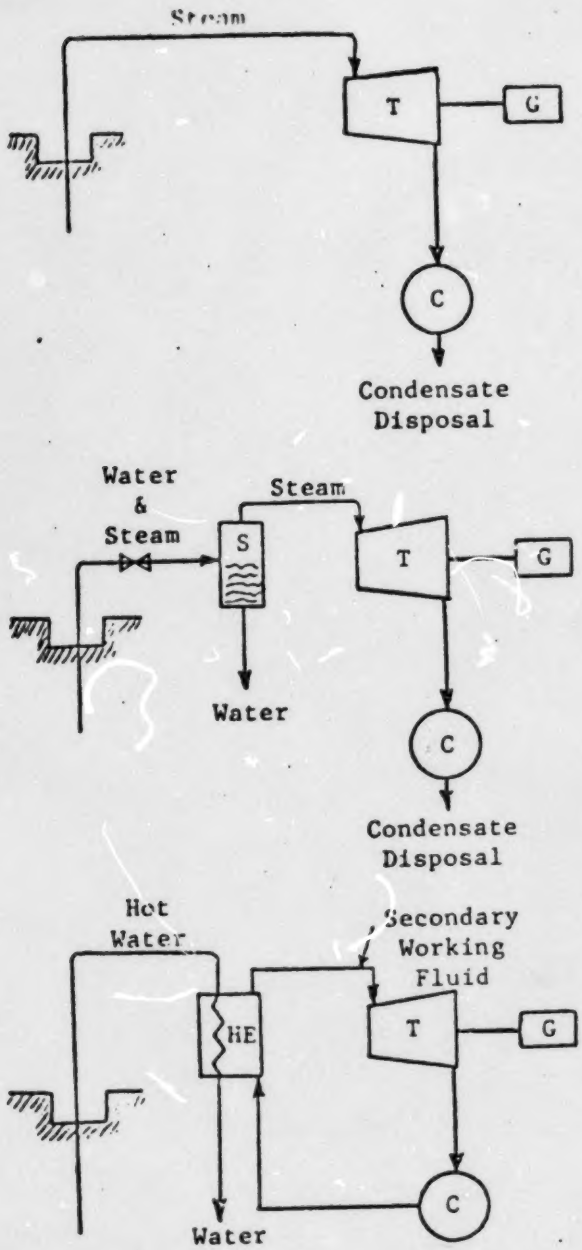
3.0 GEOTHERMAL ENERGY UTILIZATION

As discussed in Section 1.0, geothermal energy, depending on its quality, can be used for electricity generation or for non-electrical application. The quality of geothermal energy is determined by its temperature and pressure. The higher these variables the higher the quality of the energy. It is noted that impurities present in the geothermal fluid can sometimes make the fluid properties deviate greatly from those of pure water and pure steam. However, since this account is intended as an introduction to geothermal energy, geothermal fluid will be taken as pure water and/or steam. In fact, most of the hydrothermal resources developed and utilized to date are relatively clean and the use of pure fluid properties in designs has had reasonable success.

3.1 Electricity Generation from Geothermal Energy

Depending on the state of the fluid leaving the well head, there are three types of geothermal power plants:

* Dry Steam Plant - Here the fluid coming out of the well has such temperature and pressure that it is entirely steam. The system is called a dry steam plant. The steam leaving the well head is piped directly onto a steam turbine to push the turbine blades into rotary motion and therefore provide mechanical work for turning an electricity alternator which generates electricity. The process if shown in Figure 3a.



DRY STEAM PLANT

Dry steam from well expands through turbine T to drive generator G. Exhaust enters condenser C or vented to atmosphere. Condensate is disposed via evaporating pond or injection well.

FLASH STEAM PLANT

Similar to steam plant except that wet steam from well must pass through separators.

BINARY PLANT

Water is used as heat source at heat exchanger HE for a power cycle of a secondary fluid.

FIG. 3: Sketches of three types of geothermal power plants currently installed.

* Flash Steam Plant: If the geothermal fluid temperature and pressure are such that the fluid would be a mixture of steam and water as it is released, water must be removed before the steam can be piped onto the steam turbine. Since the steam in this case is in contact with water before it enters the turbine, it is assumed to be in equilibrium with water and is therefore saturated steam. Similarly, the water being removed is also in contact with its vapor phase and hence is saturated water. Since the separation of steam from water at a sudden decrease in pressure is called a flashing process, the system is called a flash steam plant. Steam, after being separated from the water, is piped onto the turbine for electricity generation in the same manner as in the dry steam plant. The water leaving the separator can either be disposed of (single flash) or be fed into a flasher where lower pressure steam is flashed off (double flash) and enters a low pressure turbine for additional power production. The process is shown in Figure 3b.

* Binary Plant: In binary plants, the water is pumped up the well by a down-hole pump which maintains a high pressure in the water to prevent flashing. The water is passed through a heat exchanger where it delivers its available heat to a secondary fluid called the working fluid. The working fluid is usually an organic liquid selected for certain desired thermodynamic properties. The working fluid is boiled to become vapor as it absorbs the geothermal heat and then enters the turbine to deliver mechanical work. After expanding through the turbine the working fluid vapor is cooled and condensed to liquid by a stream of cooling water. The condensed working fluid is then pumped back to the heat exchanger where it again absorbs the geothermal heat and repeats the cycle. The working fluid cycle is a closed cycle, called a Rankine power cycle. The geothermal fluid, after it delivers its heat to the working fluid, is usually reinjected into the ground to avoid environmental problems. The process is shown in Figure 3c.

Regardless of the plant type, the final electrical energy output is of course always smaller than the maximum work calculated from Section 2.0. The ratio between the actual electrical output and the maximum work is called the utilization efficiency:

$$\eta_u = \frac{\text{Net Electrical Energy Output}}{(H-H_o) - T_o (S - S_o)} \qquad (11)$$

where the net output is defined as the energy remaining after power requirements for the operation of the cycle have been accounted for. From the above equation η_u is always smaller than 1.00 and varies from as low as 0.2 to 0.75 depending on the type of plant, geothermal fluid temperature, and, for a binary plant, the characteristics of the working fluid.

In the process of designing a power plant, it is natural to design the cycle so that η_u is as high as possible to reduce the number of wells to be drilled for a certain predetermined net power output. However, high η_u is often associated with more expensive equipment as illustrated in Figure 4. The process of finding the optimum design indicated by point A in Figure 4 is called optimization.

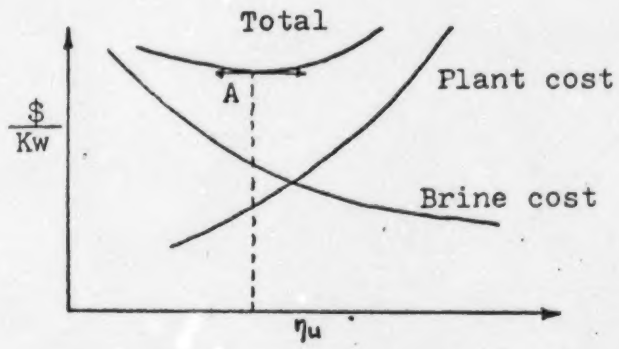


FIG. 4: Cost per unit power output as functions of utilization efficiency.

3.2 Non-Electrical Applications of Geothermal Energy

Some methods of using geothermal energy in non-electrical applications are shown in Figure 5. Three types of applications are identified:

* Indirect Heat Extraction

The amount of heat released from the geothermal fluid depends on how long the fluid remains in contact with the tube wall of the heat exchanger, across which heat is transferred. Thus in a flow situation it depends on how large the heat transfer surface is. The rules are: the larger the area the higher the amount of heat transferred, but at the same time the more expensive the heat exchanger. Thus, the money invested in extra large heat transfer area to extract the last few percent of the heat from geothermal fluid might not be justified. The utilization efficiency here is defined as:

$$\eta_u = \frac{H - H_1}{H - H_0} \qquad (12)$$

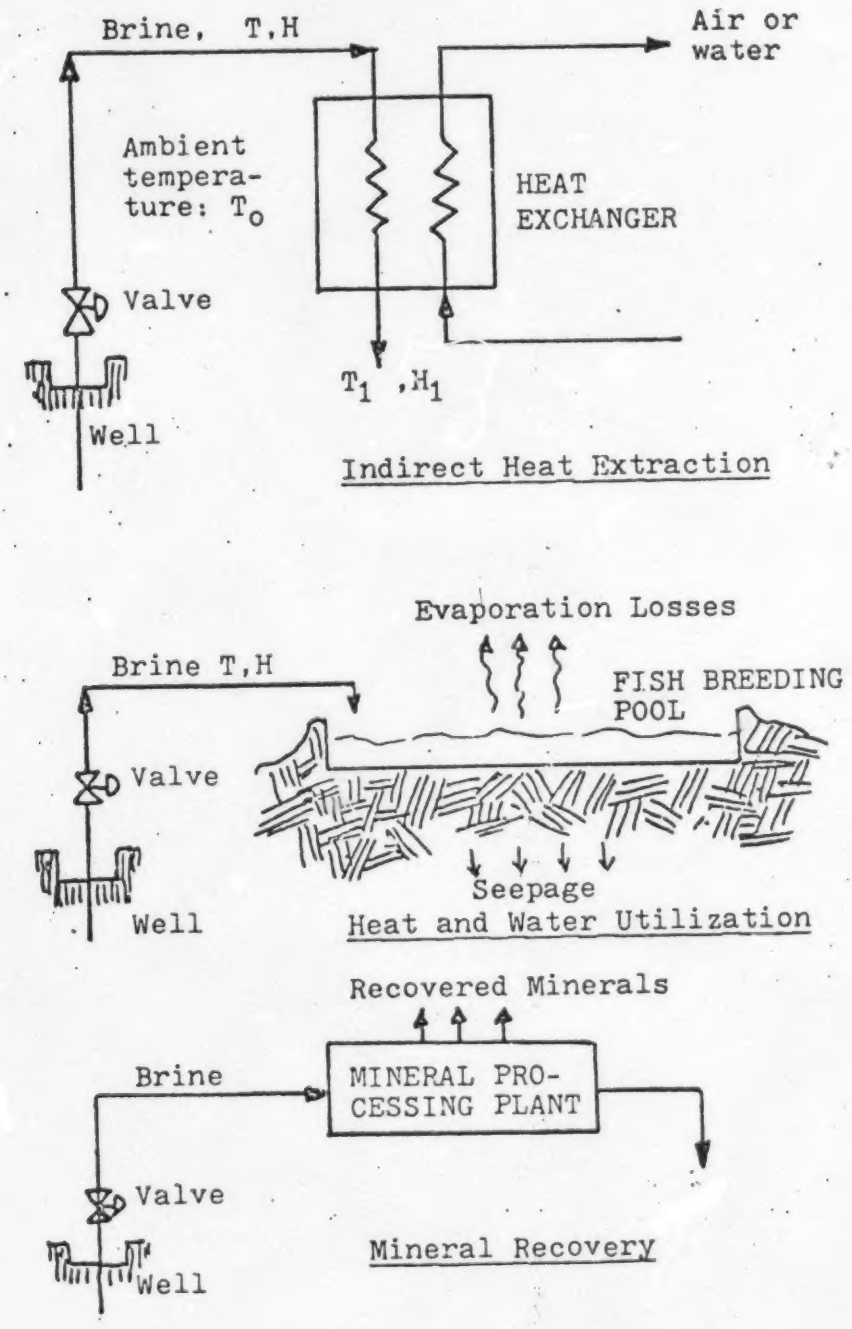


FIG. 5: Typical types of non-electrical applications

* Utilization of Heat and Water

This includes such applications as fish farming, warm water irrigation, animal husbandry, etc. Here both heat and water are utilized.

* Mineral Recovery

This type of application is aimed at realizing the commercial value of the minerals contained in the geothermal fluid. The sales of the recovered minerals must exceed the costs of wells and mineral processing operations.

QUESTIONS

3.1 Describe three types of geothermal power plants currently in operation.

3.2 The geothermal resource near the Raft River of Idaho Falls produces saturated water at 300°F. If a power plant is to be fueled by this water and can be designed to have a utilization efficiency of 60.9%, what is the required brine flow rate assuming that the rejection temperature is 80°F?

3.3 If the fluid in question 3.2 is used for heating a library complex nearby, what is its rejection temperature for a 90% utilization efficiency?

3.4 In the process of designing a geothermal power plant, the following data are available:

	Cost ($/Kw)	
η_u	Brine	Plant
0.2	800	120
0.4	340	140
0.6	200	190
0.8	120	480
1.0	100	

What is the optimum utilization efficiency and the corresponding cost in $/Kw?

REFERENCES

1. Van Thanh Nguyen, "Heat Pump and Geothermal Energy", paper presented at the 4th Annual Heat Pump Technology Conference, Oklahoma State University, Stillwater, Oklahoma, April 9-10, 1979.

2. Ronald Dipippo, "A Summary of the Technical Specifications of the Geothermal Power Plants in the World", Report COO-4051-14, Brown University, Providence, Rhode Island, February, 1978.

3. J. H. Howard, "Present Status and Future Prospects for Non-Electrical Uses of Geothermal Resources", Report UCRL-51926, Lawrence Livermore, California, October, 1975.

4. A. J. Ellis and W. A. J. Mahon, "Chemistry and Geothermal Systems", Academic Press, New York, 1977.

RECOMMENDED READINGS

1. Katherine F. Meadows, "Geothermal World Directory", 1977/78 Edition, Geothermal World Publications, 18014 Sherman Way, Suite 169, Reseda, California, 1977.

2. Stanley L. Milora and Jefferson W. Tester, "Geothermal Energy as a Source of Electric Power", The MIT Press, Cambridge, Massachusetts, 1976.

3. Edward R. Berman, "Geothermal Energy", Energy Technology Review N. 4, Noyes Data Corporation, Park Ridge, New Jersey, 1975.

APPENDICES

APPENDIX A

TABLES OF MEASUREMENT

Length and area

1 statute mile (mi)	=1760 yards =5280 feet =1.609 kilometers
1 yard (yd)	=3 feet =0.914 meter
1 foot (ft)	=12 inches =30.48 centimeters
1 inch (in.)	=25.40 millimeters
100 ft per min	=0.508 meter per sec
1 square mile	=640 acres =259 hectares
1 acre	=4840 sq yards =0.4047 hectare
1 square yard	=9 sq feet =0.836 sq meter
1 square foot	=144 sq inches =0.0929 sq meter
1 square inch	=6.45 sq centimeters
1 sq. meter (sq m)	=10,000 sq centimeters =1.196 sq yards =10.76 sq feet
1 sq centimeter (sq cm)	=100 sq millimeters =0.1550 sq inch

1 nautical mile = 6080 feet = 1.853 kilometers
1 nautical mile per hour = 1 knot

Weight

1 U.S. long ton	=2240 pounds =1016 kilograms
1 U.S. short ton	=2000 pounds =907 kilograms
1 pound (lb)	=16 ounces =7000 grains =0.454 kilogram
1 ounce (oz)	=0.0625 pound =28.35 grams

1 kilometer (km)	=1000 meters =0.621 statute mile
1 meter (m)	=100 centimeters (cm) =1000 millimeters (mm) =1.094 yards =3.281 feet =39.37 inches
1 micron	=0.001 millimeter =0.000039 inch
1 meter per sec	=196.9 ft per min
1 sq kilometer (sq km	=100 hectares =0.3861 sq mile
1 hectare (ha)	=10,000 sq meters =2.471 acres

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1 grain	=64.8 milligrams =0.0023 ounce
1 pound per foot	=1.488 kg per meter
1 metric ton (tonne)	=1000 kilograms =0.984 long ton =1.102 U.S. short tons =2205 pounds
1 gram (g)	=1000 milligrams (mg) =0.03527 ounce =15.43 grains
1 kg per meter	=0.672 pound per ft

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Volume

1 cubic yard	=27 cubic feet
	=0.765 cubic meter
1 cubic foot	=1728 cubic inches
	=28.32 liters
1 cubic inch	=16.39 cu centimeters (cu cm)
1 imperial gallon	=277.4 cubic inches
	=4.55 liters
1 U.S. gallon	=0.833 imperial gallon
	=3.785 liters
	=231 cubic inches
1 U.S. barrel (petroleum)	=42 U.S. gallons
	=35 imperial gallons
1 cu meter (cu m)	=1000 liters
	=1.308 cubic yards
0.0703 kilograms per sq mm	
	=35.31 cubic feet
1 liter	=1000 cu centimeters (cc)
	=0.2200 imperial gallon
	=0.2642 U.S. gallon
	=61.0 cubic inches
1 board foot	=12 in. x 12 in. x 1 in. thick
	=144 cubic inches

Pressure

1 atmosphere	=760 mm (29.92 in.) mercury with density 13.595 grams per cc
	=14.696 pounds per square inch
	=1.033 kg per sq cm
	=1013 millibars
1 atmosphere (metric)	=1 kg per sq cm
	=10,000 kg per sq m
	=10 m head of water
	=14.22 lb per sq in.
1 bar (megadyne per sq cm)	=1000 millibars
	=750.1 mm head of mercury
	=1.02 kg per sq cm
	=14.50 lb per sq in.
1 lb per square foot	=0.1924 in. of water
	=4.88 kilograms per sq m
1 lb per square inch	=2.036 in. head of mercury
	=2.309 ft head of water
	=0.0703 kilogram per sq cm
	=0.0690 bar
1 ton per square inch	=1.406 kilograms per square mm
1 inch head of water	=5.20 pounds per sq ft
1 foot head of water	=0.433 pound per sq in.
1 m head of water	=0.1 kg per sq cm

Volume

1 cu ft per min	=1.699 cu m per hour
1 cu m per hour	=0.589 cu ft per min

Density

1 cu ft per lb	=0.0624 cu m per kg
1 lb per cu ft	=16.02 kg per cu m
1 grain per cu ft	=2.288 grams per cu m
1 grain per U.S. gallon	=17.11 grams per cu m =17.11 milligrams/liter
1 cu m per kilogram	=16.02 cu ft per lb
1 kilogram per cu m	=0.0624 lb per cu ft
1 gram per cu m	=0.437 grain per cu ft =0.0584 grains per U.S. gal
1 gram per liter	=58.4 grain per U.S. gal

Water at 62 F (16.7 C)

1 cubic foot	=62.3 lb
1 lb	=0.01604 cu ft
1 U.S. gal	=8.33 lb

Pressure

1 in. head of mercury	=0.491 pound per sq in
1 m head of mercury	=1.360 kg per sq cm =1333 millibars
1 kilogram per sq m	=1 mm head of water =0.2048 lb per sq ft
1 kilogram per sq cm	=735.5 mm of mercury =0.981 bar =14.22 lb per sq in.
1 kg per sq mm	=0.711 ton per sq

In these conversions, inches and feet of water are measured at 62 F (16.7 C), millimeters and meters of water at 39.2 F (4 C), and inches and meters of mercury at 32 F (0 C).

Heat, work, and power

The British therm unit (Btu) or the kilogram-Calorie (Cal) were originally defined as the heat required to raise the temperatures of 1 pound or 1 kilogram of water by 1 F or 1 C, respectively. Recently the International Calorie has been defined as 1/860 International kilowatt-hour. The Btu is derived from the International

Water at 39.2 F (4 C) maximum density

1 cubic foot	=62.4 pounds
1 cubic meter	=1000 kilograms
1 pound	=0.01602 cubic foot
1 liter	=1.0 kilogram

1 kg per cu m = 1 gram per liter = 1 part per thousand

1 g per cu m = 1 mg per liter = 1 part per million (ppm)

Heat, work, and power cont'd.

Calorie from the relation 1 Cal per kg = 1.8 Btu per lb. The differences are less than 0.05 of 1% and are therefore, for the purposes of these tables, negligible.

1 British thermal unit (Btu)	= 778.17 foot-pounds (778) = 107.6 kilogram-meters = 0.2520 Calorie
1 Btu per lb	= 0.556 Calorie per kg
1 Btu per cu ft	= 8.90 Cal per cu meter
1 Btu per sq ft	= 2.712 Cal per sq meter
1 Btu per sq ft, F	= 4.88 Cal per sq m, C
1 Btu/hr, sq ft, F/in	= 1.488 Cal/hr, sq m, C/m
1 therm	= 100,000 Btu
1 Calorie (Cal)	= 3088 foot-pounds = 427 kilogram-meters = 3.968 Btu
1 Cal per kilogram	= 1.8 Btu per pound
1 Cal per cu meter	= 0.1124 Btu per cu foot
1 Cal per sq meter	= 0.3687 Btu per sq foot

Heat, work, and power cont'd.

1 Cal/sq meter, C	=0.2048 Btu/sq ft, F
1 Cal/hr, sq m, C/m	=0.672 Btu/hr, sq ft, F/ft =8.06 Btu/hr, sq ft, F/in.
1 electrical unit	=1 kilowatt-hour
1 foot-pound (ft lb)	=0.1383 kilogram-meter
1 kilogram-meter (kg m)	=7.23 foot-pounds
1 kilowatt (kw)	=738 foot-pounds per sec =102 kilogram-meters per sec =1.341 horsepower =1.360 metric horsepower
1 horsepower (hp)	=33,000 foot-pounds per min =550 foot-pounds per sec =76.04 kilogram-meters per sec =0.746 kilowatt =1.014 horsepower
1 metric horsepower	=32,550 foot-pounds per min =552 foot-pounds per sec =75 kilogram-meters per sec =0.735 kilowatt =0.986 metric horsepower
1 kilowatt-hour (kwhr)	=3412.14 Btu (3412) =860 Calories
1 horsepower-hour	=2545.1 Btu (2545)
1 metric horsepower-hour	=632 Calories
1 lb per horsepower-hour	=0.447 kg per metric hp-hr
1 kg per metric hp-hour	=2.235 lb per horsepower-hr

APPENDIX B

Note: The following steam tables have been abstracted from *Thermodynamic and Transport Properties of Steam* (Copyright, 1967, by The American Society of Mechanical Engineers.)

Table 1
Properties of saturated steam and saturated water (temperature)

Temp F	Press. psia	Volume, ft³/lb			Enthalpy, Btu/lb			Entropy, Btu/lb x F			Temp F
		Water v_f	Evap v_{fg}	Steam v_g	Water h_f	Evap h_{fg}	Steam h_g	Water s_f	Evap s_{fg}	Steam s_g	
32	0.08859	0.01602	3305	3305	-0.02	1075.5	1075.5	0.0000	2.1873	2.1873	32
35	0.09991	0.01602	2948	2948	3.00	1073.8	1076.8	0.0061	2.1706	2.1767	35
40	0.12163	0.01602	2446	2446	8.03	1071.0	1079.0	0.0162	2.1432	2.1594	40
45	0.14744	0.01602	2037.7	2037.8	13.04	1068.1	1081.2	0.0262	2.1164	2.1426	45
50	0.17796	0.01602	1704.8	1704.8	18.05	1065.3	1083.4	0.0361	2.0901	2.1262	50
60	0.2561	0.01603	1207.6	1207.6	28.06	1059.7	1087.7	0.0555	2.0391	2.0946	60
70	0.3629	0.01605	868.3	868.4	38.05	1054.0	1092.1	0.0745	1.9900	2.0645	70
80	0.5068	0.01607	633.3	633.3	48.04	1048.4	1096.4	0.0932	1.9426	2.0359	80
90	0.6981	0.01610	468.1	468.1	58.02	1042.7	1100.8	0.1115	1.8970	2.0086	90
100	0.9492	0.01613	350.4	350.4	68.00	1037.1	1105.1	0.1295	1.8530	1.9825	100
110	1.2750	0.01617	265.4	265.4	77.98	1031.4	1109.3	0.1472	1.8105	1.9577	110
120	1.6927	0.01620	203.25	203.26	87.97	1025.6	1113.6	0.1646	1.7693	1.9339	120
130	2.2230	0.01625	157.32	157.33	97.96	1019.8	1117.8	0.1817	1.7295	1.9112	130
140	2.8892	0.01629	122.98	123.00	107.95	1014.0	1122.0	0.1985	1.6910	1.8895	140
150	3.718	0.01634	97.05	97.07	117.95	1008.2	1126.1	0.2150	1.6536	1.8686	150
160	4.741	0.01640	77.27	77.29	127.96	1002.2	1130.2	0.2313	1.6174	1.8487	160
170	5.993	0.01645	62.04	62.06	137.97	996.2	1134.2	0.2473	1.5822	1.8295	170
180	7.511	0.01651	50.21	50.22	148.00	990.2	1138.2	0.2631	1.5480	1.8111	180
190	9.340	0.01657	40.94	40.96	158.04	984.1	1142.1	0.2787	1.5148	1.7934	190
200	11.526	0.01664	33.62	33.64	168.09	977.9	1146.0	0.2940	1.4824	1.7764	200
210	14.123	0.01671	27.80	27.82	178.15	971.6	1149.7	0.3091	1.4509	1.7600	210
212	14.696	0.01672	26.78	26.80	180.17	970.3	1150.5	0.3121	1.4447	1.7568	212
220	17.186	0.01678	23.13	23.15	188.23	965.2	1153.4	0.3241	1.4201	1.7442	220
230	20.779	0.01685	19.364	19.381	198.33	958.7	1157.1	0.3388	1.3902	1.7290	230
240	24.963	0.01693	16.304	16.321	208.45	952.1	1160.6	0.3533	1.3609	1.7142	240
250	29.825	0.01701	13.802	13.819	218.59	945.4	1164.0	0.3677	1.3323	1.7000	250
260	35.427	0.01709	11.745	11.762	228.76	938.6	1167.4	0.3819	1.3043	1.6862	260
270	41.856	0.01718	10.042	10.060	238.95	931.7	1170.6	0.3960	1.2769	1.6729	270
280	49.200	0.01726	8.627	8.644	249.17	924.6	1173.8	0.4098	1.2501	1.6599	280
290	57.550	0.01738	7.443	7.460	259.4	917.4	1176.8	0.4236	1.2238	1.6473	290
300	67.005	0.01745	6.448	6.466	269.7	910.0	1179.7	0.4372	1.1979	1.6351	300
310	77.67	0.01755	5.609	5.626	280.0	902.5	1182.5	0.4506	1.1726	1.6232	310
320	89.64	0.01766	4.896	4.914	290.4	894.8	1185.2	0.4640	1.1477	1.6116	320
340	117.99	0.01787	3.770	3.788	311.3	878.8	1190.1	0.4902	1.0990	1.5892	340
360	153.01	0.01811	2.939	2.957	332.3	862.1	1194.4	0.5161	1.0517	1.5678	360
380	195.73	0.01836	2.317	2.335	353.6	844.5	1198.0	0.5416	1.0057	1.5473	380
400	247.26	0.01864	1.8444	1.8630	375.1	825.9	1201.0	0.5667	0.9607	1.5274	400
420	308.78	0.01894	1.4808	1.4997	396.9	806.2	1203.1	0.5915	0.9165	1.5080	420
440	381.54	0.01926	1.1976	1.2169	419.0	785.4	1204.4	0.6161	0.8729	1.4890	440
460	456.9	0.0196	0.9746	0.9942	441.5	763.2	1204.8	0.6405	0.8299	1.4704	460
480	566.2	0.0200	0.7972	0.8172	464.5	739.6	1204.1	0.6648	0.7871	1.4518	480
500	680.9	0.0204	0.6545	0.6749	487.9	714.3	1202.2	0.6890	0.7443	1.4333	500
520	812.5	0.0209	0.5386	0.5596	512.0	687.0	1199.0	0.7133	0.7013	1.4146	520
540	962.8	0.0215	0.4437	0.4651	536.8	657.5	1194.3	0.7378	0.6577	1.3954	540
560	1133.4	0.0221	0.3651	0.3871	562.4	625.3	1187.7	0.7625	0.6132	1.3757	560
580	1326.2	0.0228	0.2994	0.3222	589.1	589.9	1179.0	0.7876	0.5673	1.3550	580
600	1543.2	0.0236	0.2438	0.2675	617.1	550.6	1167.7	0.8134	0.5195	1.3330	600
620	1786.9	0.0247	0.1962	0.2208	646.9	506.3	1153.2	0.8403	0.4689	1.3092	620
640	2059.9	0.0260	0.1543	0.1802	679.1	454.6	1133.7	0.8686	0.4134	1.2821	640
660	2365.7	0.0277	0.1166	0.1443	714.9	392.1	1107.0	0.8995	0.3502	1.2498	660
680	2708.6	0.0304	0.0808	0.1112	758.5	310.1	1068.5	0.9365	0.2720	1.2086	680
700	3094.3	0.0366	0.0386	0.0752	822.4	172.7	995.2	0.9901	0.1490	1.1390	700
705.5	3208.2	0.0508	0	0.0508	906.0	0	906.0	1.0612	0	1.0612	705.5

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Table 2
Properties of saturated steam and saturated water (pressure)

Press. psia	Temp F	Volume, ft³/lb			Enthalpy, Btu/lb			Entropy, Btu/lb x F			Energy, Btu/lb		Press. psia
		Water	Evap	Steam	Water	Evap	Steam	Water	Evap	Steam	Water	Steam	
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	u_f	u_g	
0.0886	32.018	0.01602	3302.4	3302.4	0.00	1075.5	1075.5	0	2.1872	2.1872	0	1021.3	0.0886
0.10	35.023	0.01602	2945.5	2945.5	3.03	1073.8	1076.8	0.0061	2.1705	2.1766	3.03	1022.3	0.10
0.15	45.453	0.01602	2004.7	2004.7	13.50	1067.9	1061.4	0.0271	2.1140	2.1411	13.50	1025.7	0.15
0.20	53.160	0.01603	1526.3	1526.3	21.22	1063.5	1084.7	0.0422	2.0738	2.1160	21.22	1028.3	0.20
0.30	64.484	0.01604	1039.7	1039.7	32.54	1057.1	1089.7	0.0641	2.0168	2.0809	32.54	1032.0	0.30
0.40	72.869	0.01606	792.0	792.1	40.92	1052.4	1093.3	0.0799	1.9762	2.0562	40.92	1034.7	0.40
0.5	79.586	0.01607	641.5	641.5	47.62	1048.6	1096.3	0.0925	1.9446	2.0370	47.62	1036.9	0.5
0.6	85.218	0.01609	540.0	540.1	53.25	1045.5	1098.7	0.1028	1.9186	2.0215	53.24	1038.7	0.6
0.7	90.09	0.01610	466.93	466.94	58.10	1042.7	1100.8	0.3	1.5986	2.0263	58.10	1040.3	0.7
0.8	94.38	0.01611	411.67	411.69	62.39	1040.3	1102.6	0.1117	1.8775	1.9970	62.39	1041.7	0.8
0.9	98.24	0.01612	368.41	368.43	66.24	1038.1	1104.3	0.1264	1.8606	1.9870	66.24	1042.9	0.9
1.0	101.74	0.01614	333.59	333.60	69.73	1036.1	1105.8	0.1326	1.8455	1.9781	69.73	1044.1	1.0
2.0	126.07	0.01623	173.74	173.76	94.03	1022.1	1116.2	0.1750	1.7450	1.9200	94.03	1051.8	2.0
3.0	141.47	0.01630	118.71	118.73	109.42	1013.2	1122.6	0.2009	1.6854	1.8864	109.41	1056.7	3.0
4.0	152.96	0.01636	90.63	90.64	120.92	1006.4	1127.3	0.2199	1.6428	1.8626	120.90	1060.2	4.0
5.0	162.24	0.01641	73.515	73.53	130.20	1000.9	1131.1	0.2349	1.6094	1.8443	130.18	1063.1	5.0
6.0	170.05	0.01645	61.957	61.98	138.03	996.2	1134.2	0.2474	1.5820	1.8294	138.01	1065.4	6.0
7.0	176.84	0.01649	53.634	53.65	144.83	992.1	1136.9	0.2581	1.5587	1.8168	144.81	1067.4	7.0
8.0	182.86	0.01653	47.328	47.35	150.87	988.5	1139.3	0.2676	1.5384	1.8060	150.84	1069.2	8.0
9.0	188.27	0.01656	42.385	42.40	156.30	985.1	1141.4	0.2760	1.5204	1.7964	156.28	1070.8	9.0
10	193.21	0.01659	38.404	38.42	161.26	982.1	1143.3	0.2836	1.5043	1.7879	161.23	1072.3	10
14.696	212.00	0.01672	26.782	26.80	180.17	970.3	1150.5	0.3121	1.4447	1.7568	180.12	1077.6	14.696
15	213.03	0.01673	25.274	26.29	181.21	969.7	1150.9	0.3137	1.4415	1.7552	181.16	1077.9	15
20	227.96	0.01683	20.070	20.087	196.27	960.1	1155.3	0.3358	1.3962	1.7320	196.21	1082.0	20
30	250.34	0.01701	13.7265	13.744	218.9	945.2	1164.1	0.3682	1.3313	1.6995	218.8	1087.9	30
40	267.25	0.01715	10.4794	10.497	236.1	933.6	1169.8	0.3921	1.2844	1.6765	236.0	1092.1	40
50	281.02	0.01727	8.4967	8.514	250.2	923.9	1174.1	0.4112	1.2474	1.6586	250.1	1095.3	50
60	292.71	0.01738	7.1562	7.174	262.2	915.4	1177.6	0.4273	1.2167	1.6440	262.0	1098.0	60
70	302.93	0.01748	6.1875	6.205	272.7	907.8	1180.6	0.4411	1.1905	1.6316	272.5	1100.2	70
80	312.04	0.01757	5.4536	5.471	282.1	900.9	1183.1	0.4534	1.1675	1.6209	281.9	1102.1	80
90	320.28	0.01766	4.8777	4.895	290.7	894.6	1185.3	0.4643	1.1470	1.6113	290.4	1103.7	90
100	327.82	0.01774	4.4133	4.431	298.5	888.6	1187.2	0.4743	1.1284	1.6027	298.2	1105.2	100
120	341.27	0.01789	3.7097	3.728	312.6	877.8	1190.4	0.4919	1.0960	1.5879	312.2	1107.6	120
140	353.04	0.01803	3.2010	3.219	325.0	868.0	1193.0	0.5071	1.0681	1.5752	324.5	1109.6	140
160	363.55	0.01815	2.8155	2.834	336.1	859.0	1195.1	0.5206	1.0435	1.5641	335.5	1111.2	160
180	373.08	0.01827	2.5129	2.531	346.2	850.7	1196.9	0.5328	1.0215	1.5543	345.6	1112.5	180
200	381.80	0.01639	2.2689	2.287	355.5	842.8	1198.3	0.5438	1.0016	1.5454	354.8	1113.7	200
250	400.97	0.01865	1.8245	1.8432	376.1	825.0	1201.1	0.5679	0.9585	1.5264	375.3	1115.8	250
300	417.35	0.01889	1.5238	1.5427	394.0	808.9	1202.9	0.5882	0.9223	1.5105	392.9	1117.2	300
350	431.73	0.01913	1.3064	1.3255	409.8	794.2	1204.0	0.6059	0.8909	1.4968	408.6	1118.1	350
400	444.60	0.0193	1.14162	1.1610	424.2	780.4	1204.6	0.6217	0.8630	1.4847	422.7	1118.7	400
450	456.28	0.0195	1.01224	1.0318	437.3	767.5	1204.8	0.6360	0.8378	1.4738	435.7	1118.9	450
500	467.01	0.0198	0.90787	0.9276	449.5	755.1	1204.7	0.6490	0.8149	1.4639	447.7	1118.8	500
550	476.94	0.0199	0.82183	0.8418	460.9	743.3	1204.3	0.6611	0.7935	1.4547	459.9	1118.6	550
600	486.20	0.0201	0.74962	0.7698	471.7	732.0	1203.7	0.6723	0.7738	1.4461	469.5	1118.2	600
700	503.08	0.0205	0.63505	0.6556	491.6	710.2	1201.8	0.6928	0.7377	1.4304	488.9	1116.9	700
800	518.21	0.0209	0.54809	0.5690	509.8	689.6	1199.4	0.7111	0.7051	1.4163	506.7	1115.2	800
900	531.95	0.0212	0.47968	0.5009	526.7	669.7	1196.4	0.7279	0.6753	1.4032	523.2	1113.0	900
1000	544.58	0.0216	0.42436	0.4460	542.6	650.4	1192.9	0.7434	0.6476	1.3910	538.6	1110.4	1000
1100	556.28	0.0220	0.37863	0.4006	557.5	631.5	1189.1	0.7578	0.6216	1.3794	553.1	1107.5	1100
1200	567.19	0.0223	0.34013	0.3635	571.9	613.0	1184.8	0.7714	0.5969	1.3683	566.9	1104.3	1200
1300	577.42	0.0227	0.30722	0.3299	585.6	594.6	1180.2	0.7843	0.5733	1.3577	580.1	1100.9	1300
1400	587.07	0.0231	0.27871	0.3018	598.8	576.5	1175.3	0.7966	0.5507	1.3474	592.9	1097.1	1400
1500	596.20	0.0235	0.25372	0.2772	611.7	558.4	1170.1	0.8085	0.5288	1.3373	605.2	1093.1	1500
2000	635.80	0.0257	0.16766	0.1883	672.1	466.2	1138.3	0.8625	0.4256	1.2881	662.6	1068.6	2000
2500	668.11	0.0286	0.10209	0.1307	731.7	361.6	1093.3	0.9139	0.3206	1.2345	718.5	1032.9	2500
3000	695.33	0.0343	0.05073	0.0850	801.8	218.4	1020.3	0.9728	0.1891	1.1619	782.8	973.1	3000
3208.2	705.47	0.0508	0	0.0508	906.0	0	906.0	1.0612	0	1.0612	875.9	875.9	3208.2

BEST COPY AVAILABLE

Table 3
Properties of superheated steam and compressed water (temperature and pressure)

Abs press. lb/sq in. (sat. temp)		Temperature, F													
		100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
	v	0.0161	392.5	452.3	511.9	571.5	631.1	690.7								
1	h	68.00	1150.2	1195.7	1241.8	1288.6	1336.1	1384.5								
(101.74)	s	0.1295	2.0509	2.1152	2.1722	2.2237	2.2708	2.3144								
	v	0.0161	78.14	90.24	102.24	114.21	126.15	138.08	150.01	161.94	173.86	185.78	197.70	209.62	221.53	233.45
5	h	68.01	1148.6	1194.8	1241.3	1288.2	1335.9	1384.3	1433.6	1483.7	1534.7	1586.7	1639.6	1693.3	1748.0	1803.5
(162.24)	s	0.1295	1.8716	1.9369	1.9943	2.0460	2.0932	2.1369	2.1776	2.2159	2.2521	2.2866	2.3194	2.3509	2.3811	2.4101
	v	0.0161	38.84	44.98	51.03	57.04	63.03	69.00	74.98	80.94	86.91	92.87	98.84	104.80	110.76	116.72
10	h	68.02	1146.6	1193.7	1240.6	1287.6	1335.5	1384.0	1433.4	1483.5	1534.6	1586.6	1639.5	1693.3	1747.9	1803.4
(193.21)	s	0.1295	1.7926	1.8593	1.9173	1.9692	2.0166	2.0603	2.1011	2.1394	2.1757	2.2101	2.2430	2.2744	2.3046	2.3337
	v	0.0161	0.0166	29.899	33.963	37.985	41.986	45.978	49.964	53.946	57.926	61.905	65.882	69.858	73.833	77.807
15	h	68.04	168.09	1192.5	1239.9	1287.3	1335.2	1383.8	1433.2	1483.4	1534.5	1586.5	1639.4	1693.2	1747.8	1803.4
(213.03)	s	0.1295	0.2940	1.8134	1.8720	1.9242	1.9717	2.0155	2.0563	2.0946	2.1309	2.1653	2.1982	2.2297	2.2599	2.2890
	v	0.0161	0.0166	22.356	25.428	28.457	31.466	34.465	37.458	40.447	43.435	46.420	49.405	52.388	55.370	58.352
20	h	68.05	168.11	1191.4	1239.2	1286.9	1334.9	1383.5	1432.9	1483.2	1534.3	1586.3	1639.3	1693.1	1747.8	1803.3
(227.96)	s	0.1295	0.2940	1.7808	1.8397	1.8921	1.9397	1.9836	2.0244	2.0628	2.0991	2.1336	2.1665	2.1979	2.2282	2.2572
	v	0.0161	0.0166	11.036	12.624	14.165	15.685	17.195	18.699	20.199	21.697	23.194	24.689	26.183	27.676	29.168
40	h	68.10	168.15	1186.6	1236.4	1285.0	1333.6	1382.5	1432.1	1482.5	1533.7	1585.8	1638.8	1692.7	1747.5	1803.0
(267.25)	s	0.1295	0.2940	1.6992	1.7606	1.8143	1.8624	1.9065	1.9476	1.9860	2.0224	2.0569	2.0899	2.1224	2.1515	2.1807
	v	0.0161	0.0166	7.257	8.354	9.400	10.425	11.438	12.446	13.450	14.452	15.452	16.450	17.448	18.445	19.441
60	h	68.15	168.20	1181.6	1233.5	1283.2	1332.3	1381.5	1431.3	1481.8	1533.2	1585.3	1638.4	1692.4	1747.1	1802.8
(292.71)	s	0.1295	0.2939	1.6492	1.7134	1.7681	1.8168	1.8612	1.9024	1.9410	1.9774	2.0120	2.0450	2.0765	2.1068	2.1359
	v	0.0161	0.0166	0.0175	6.218	7.018	7.794	8.560	9.319	10.075	10.829	11.581	12.331	13.081	13.829	14.577
80	h	68.21	168.25	269.74	1230.5	1281.3	1330.9	1380.5	1430.5	1481.1	1532.6	1584.9	1638.0	1692.0	1746.8	1802.5
(312.04)	s	0.1295	0.2939	0.4371	1.6790	1.7349	1.7842	1.8289	1.8702	1.9089	1.9454	1.9800	2.0131	2.0446	2.0750	2.1041
	v	0.0161	0.0166	0.0175	4.935	5.588	6.216	6.833	7.443	8.050	8.655	9.258	9.860	10.460	11.060	11.659
100	h	68.26	168.29	269.77	1227.4	1279.3	1329.6	1379.5	1429.7	1480.4	1532.0	1584.4	1637.6	1691.6	1746.5	1802.2
(327.82)	s	0.1295	0.2939	0.4371	1.6516	1.7088	1.7586	1.8036	1.8451	1.8839	1.9205	1.9552	1.9883	2.0199	2.0502	2.0794
	v	0.0161	0.0166	0.0175	4.0786	4.6341	5.1637	5.6831	6.1928	6.7006	7.2060	7.7095	8.2119	8.7130	9.2134	9.7130
120	h	68.31	168.33	269.81	1224.1	1277.4	1328.1	1378.4	1428.8	1479.8	1531.4	1583.9	1637.1	1691.3	1746.2	1802.0
(341.27)	s	0.1295	0.2939	0.4371	1.6286	1.6872	1.7376	1.7829	1.8246	1.8635	1.9001	1.9349	1.9680	1.9996	2.0300	2.0592
	v	0.0161	0.0166	0.0175	3.4661	3.9526	4.4119	4.8585	5.2995	5.7364	6.1709	6.6036	7.0349	7.4652	7.8946	8.3233
140	h	68.37	168.36	269.85	1220.8	1275.3	1326.8	1377.4	1428.0	1479.1	1530.8	1583.4	1636.7	1690.9	1745.9	1801.7
(353.04)	s	0.1295	0.2939	0.4370	1.6085	1.6686	1.7196	1.7652	1.8071	1.8461	1.8828	1.9176	1.9508	1.9825	2.0129	2.0421
	v	0.0161	0.0166	0.0175	3.0060	3.4413	3.8480	4.2420	4.6295	5.0132	5.3945	5.7741	6.1522	6.5293	6.9055	7.2811
160	h	68.42	168.42	269.89	1217.4	1273.3	1325.4	1376.4	1427.2	1478.4	1530.3	1582.9	1636.3	1690.5	1745.6	1801.4
(363.55)	s	0.1294	0.2936	0.4370	1.5906	1.6522	1.7039	1.7499	1.7919	1.8310	1.8678	1.9027	1.9359	1.9676	1.9980	2.0273
	v	0.0161	0.0166	0.0174	2.6474	3.0433	3.4093	3.7621	4.1084	4.4505	4.7907	5.1289	5.4657	5.8014	6.1363	6.4704
180	h	68.47	168.47	269.92	1213.8	1271.2	1324.0	1375.3	1426.3	1477.7	1529.7	1582.4	1635.9	1690.2	1745.3	1801.2
(373.08)	s	0.1294	0.2938	0.4370	1.5743	1.6376	1.6900	1.7362	1.7784	1.8176	1.8545	1.8894	1.9227	1.9545	1.9849	2.0142
	v	0.0161	0.0166	0.0174	2.3598	2.7247	3.0583	3.3783	3.6915	4.0008	4.3077	4.6128	4.9165	5.2191	5.5209	5.8219
200	h	68.52	168.51	269.96	1210.1	1269.0	1322.6	1374.3	1425.5	1477.0	1529.1	1581.9	1635.4	1689.8	1745.0	1800.9
(381.80)	s	0.1294	0.2938	0.4369	1.5593	1.6242	1.6776	1.7239	1.7663	1.8057	1.8426	1.8776	1.9109	1.9427	1.9732	2.0025
	v	0.0161	0.0165	0.0174	0.0186	2.1504	2.4662	2.6872	2.9410	3.1909	3.4382	3.6837	3.9278	4.1709	4.4131	4.6546
250	h	68.66	168.63	270.06	375.10	1263.5	1319.0	1371.6	1423.4	1475.3	1527.6	1580.5	1634.4	1688.9	1744.2	1800.2
(400.97)	s	0.1294	0.2937	0.4368	0.5667	1.5951	1.6562	1.6976	1.7405	1.7801	1.8173	1.8524	1.8858	1.9177	1.9482	1.9776
	v	0.0161	0.0166	0.0174	0.0186	1.7665	2.0044	2.2263	2.4407	2.6509	2.8585	3.0643	3.2688	3.4721	3.6746	3.8764
300	h	68.79	168.74	270.14	375.15	1257.7	1315.2	1366.9	1421.3	1473.6	1526.2	1579.4	1633.3	1658.0	1743.4	1759.6
(417.35)	s	0.1294	0.2937	0.4307	0.5665	1.5703	1.6274	1.6758	1.7192	1.7591	1.7964	1.8317	1.8652	1.8972	1.9278	1.9572
	v	0.0161	0.0166	0.0174	0.0186	1.4913	1.7028	1.8970	2.0812	2.2652	2.4445	2.6219	2.7980	2.9730	3.1471	3.3205
350	h	68.92	168.85	270.24	375.21	1251.5	1311.4	1366.2	1419.2	1471.8	1524.7	1578.2	1632.3	1687.1	1742.6	1798.9
(431.73)	s	0.1293	0.2936	0.4367	0.5664	1.5483	1.6077	1.6571	1.7005	1.7411	1.7787	1.8141	1.8477	1.8798	1.9105	1.9400
	v	0.0161	0.0166	0.0174	0.0162	1.2841	1.4763	1.6499	1.8151	1.9759	2.1339	2.2901	2.4450	2.5987	2.7515	2.9037
400	h	69.05	168.97	270.33	375.27	1245.1	1307.4	1363.4	1417.0	1470.1	1523.3	1576.9	1631.2	1686.2	1741.9	1798.2
(444.60)	s	0.1293	0.2935	0.4366	0.5663	1.5232	1.5901	1.6406	1.6850	1.7255	1.7632	1.7988	1.8325	1.8647	1.8955	1.9250
	v	0.0161	0.0166	0.0174	0.0186	0.9919	1.1584	1.3037	1.4397	1.5708	1.6992	1.8256	1.9507	2.0746	2.1977	2.3200
500	h	69.32	169.19	270.51	375.39	1231.2	1299.1	1357.7	1412.7	1466.6	1520.3	1574.4	1629.1	1684.4	1740.3	1796.9
(467.01)	s	0.1292	0.2934	0.4364	0.5662	1.4921	1.5595	1.6123	1.6578	1.6990	1.7371	1.7730	1.8069	1.8393	1.8702	1.8998

BEST COPY AVAILABLE

Table 3
Properties of superheated steam and compressed water (temperature and pressure)

Abs press. lb/sq in. (sat. temp)		Temperature, F														
		100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
600 (486.20)	v	0.0161	0.0166	0.0174	0.0186	0.7944	0.9456	1.0726	1.1892	1.3008	1.4093	1.5160	1.6211	1.7252	1.8284	1.9309
	h	69.58	169.42	270.70	375.49	1215.9	1290.3	1351.8	1408.3	1463.0	1517.4	1571.9	1627.0	1682.6	1738.8	1795.6
	s	0.1292	0.2933	0.4362	0.5657	1.4590	1.5329	1.5844	1.6351	1.6769	1.7155	1.7517	1.7859	1.8184	1.8494	1.8792
700 (503.08)	v	0.0161	0.0166	0.0174	0.0186	0.0204	0.7928	0.9072	1.0102	1.1078	1.2023	1.2948	1.3858	1.4757	1.5647	1.6530
	h	69.84	169.65	270.89	375.61	487.93	1281.0	1345.6	1403.7	1459.4	1514.4	1569.4	1624.8	1680.7	1737.2	1794.3
	s	0.1291	0.2932	0.4360	0.5655	0.6889	1.5090	1.5673	1.6154	1.6580	1.6970	1.7335	1.7679	1.8006	1.8318	1.8617
800 (518.21)	v	0.0161	0.0166	0.0174	0.0186	0.0204	0.6774	0.7829	0.8759	0.9631	1.0470	1.1289	1.2093	1.2885	1.3669	1.4446
	h	70.11	169.88	271.07	375.73	487.88	1271.1	1339.2	1399.1	1455.8	1511.4	1566.9	1622.7	1678.9	1735.0	1792.9
	s	0.1290	0.2930	0.4358	0.5652	0.6885	1.4869	1.5484	1.5980	1.6413	1.6807	1.7175	1.7522	1.7851	1.8164	1.8464
900 (531.95)	v	0.0161	0.0166	0.0174	0.0186	0.0204	0.5869	0.6858	0.7713	0.8504	0.9262	0.9998	1.0720	1.1430	1.2131	1.2825
	h	70.37	170.10	271.26	375.84	487.83	1260.6	1332.7	1394.4	1452.2	1508.5	1564.4	1620.6	1677.1	1734.1	1791.6
	s	0.1290	0.2929	0.4357	0.5649	0.6881	1.4659	1.5311	1.5822	1.6263	1.6662	1.7033	1.7382	1.7713	1.8028	1.8329
1000 (544.58)	v	0.0161	0.0166	0.0174	0.0186	0.0204	0.5137	0.6080	0.6875	0.7603	0.8295	0.8966	0.9622	1.0266	1.0901	1.1529
	h	70.63	170.33	271.44	375.96	487.79	1249.3	1325.9	1389.6	1448.5	1504.4	1561.9	1618.4	1675.3	1732.5	1790.3
	s	0.1289	0.2928	0.4355	0.5647	0.6876	1.4457	1.5149	1.5677	1.6126	1.6530	1.6905	1.7256	1.7589	1.7905	1.8207
1100 (556.28)	v	0.0161	0.0166	0.0174	0.0185	0.0203	0.4531	0.5440	0.6188	0.6865	0.7505	0.8121	0.8723	0.9313	0.9894	1.0468
	h	70.90	170.56	271.63	376.08	487.75	1237.3	1318.8	1384.7	1444.7	1502.4	1559.4	1616.3	1673.5	1731.0	1789.0
	s	0.1289	0.2927	0.4353	0.5644	0.6872	1.4259	1.4996	1.5542	1.6000	1.6410	1.6787	1.7141	1.7475	1.7793	1.8097
1200 (567.19)	v	0.0161	0.0166	0.0174	0.0185	0.0203	0.4016	0.4905	0.5615	0.6250	0.6845	0.7418	0.7974	0.8519	0.9055	0.9584
	h	71.16	170.78	271.82	376.20	487.72	1224.2	1311.5	1379.7	1440.9	1499.4	1556.9	1614.2	1671.6	1729.4	1787.6
	s	0.1288	0.2926	0.4351	0.5642	0.6868	1.4061	1.4851	1.5415	1.5883	1.6298	1.6679	1.7035	1.7371	1.7691	1.7996
1400 (587.07)	v	0.0161	0.0166	0.0174	0.0185	0.0203	0.3176	0.4059	0.4712	0.5282	0.5809	0.6311	0.6798	0.7272	0.7737	0.8195
	h	71.68	171.24	272.19	376.44	487.65	1194.1	1296.1	1369.3	1433.2	1493.2	1551.8	1609.9	1668.0	1726.3	1785.0
	s	0.1287	0.2923	0.4348	0.5636	0.6859	1.3652	1.4575	1.5132	1.5570	1.6096	1.6484	1.6845	1.7185	1.7508	1.7815
1600 (604.87)	v	0.0161	0.0166	0.0173	0.0185	0.0202	0.0236	0.3415	0.4032	0.4555	0.5031	0.5482	0.5915	0.6336	0.6748	0.7153
	h	72.21	171.69	272.57	376.69	487.60	616.77	1279.4	1358.5	1425.2	1486.9	1546.6	1605.6	1664.3	1723.2	1782.3
	s	0.1286	0.2921	0.4344	0.5631	0.6851	0.8129	1.4312	1.4968	1.5478	1.5916	1.6312	1.6678	1.7022	1.7344	1.7657
1800 (621.02)	v	0.0160	0.0165	0.0173	0.0185	0.0202	0.0235	0.2906	0.3500	0.3988	0.4426	0.4836	0.5229	0.5609	0.5980	0.6343
	h	72.73	172.15	272.96	376.93	487.56	615.58	1261.1	1347.2	1417.1	1480.6	1541.1	1601.2	1660.7	1720.1	1779.7
	s	0.1284	0.2918	0.4341	0.5626	0.6843	0.8109	1.4054	1.4768	1.5302	1.5753	1.6156	1.6523	1.6876	1.7204	1.7516
2000 (635.80)	v	0.0160	0.0165	0.0173	0.0184	0.0201	0.0233	0.2488	0.3072	0.3534	0.3942	0.4320	0.4680	0.5027	0.5365	0.5695
	h	73.25	172.60	273.32	377.19	487.53	614.48	1240.9	1353.4	1408.7	1474.1	1536.2	1596.9	1657.0	1717.0	1777.1
	s	0.1283	0.2916	0.4337	0.5621	0.6834	0.8091	1.3794	1.4578	1.5138	1.5603	1.6014	1.6391	1.6743	1.7073	1.7389
2500 (668.11)	v	0.0160	0.0165	0.0173	0.0184	0.0200	0.0230	0.1581	0.2293	0.2712	0.3068	0.3390	0.3692	0.3980	0.4259	0.4529
	h	74.57	173.74	274.27	377.32	487.50	612.68	1176.7	1303.4	1385.7	1457.5	1522.9	1585.9	1647.8	1709.2	1770.4
	s	0.1280	0.2910	0.4329	0.5609	0.6815	0.8048	1.3076	1.4129	1.4766	1.5269	1.5703	1.6094	1.6456	1.6796	1.7116
3000 (695.33)	v	0.0160	0.0165	0.0172	0.0183	0.0200	0.0228	0.0962	0.1753	0.2161	0.2484	0.2770	0.3023	0.3282	0.3522	0.3753
	h	75.82	174.68	275.22	378.47	487.52	610.08	1050.5	1267.0	1363.2	1440.2	1509.4	1574.8	1638.5	1701.4	1763.8
	s	0.1277	0.2904	0.4320	0.5597	0.6796	0.8009	1.1966	1.3692	1.4429	1.4976	1.5434	1.5841	1.6214	1.6561	1.6888
3200 (705.08)	v	0.0160	0.0165	0.0172	0.0183	0.0199	0.0227	0.0335	0.1593	0.1987	0.2301	0.2576	0.2827	0.3065	0.3291	0.3510
	h	76.4	175.3	275.5	378.7	487.5	609.4	800.8	1250.9	1353.4	1433.1	1503.8	1570.3	1634.8	1698.3	1761.2
	s	0.1276	0.2902	0.4317	0.5592	0.6788	0.7994	0.9708	1.3515	1.4300	1.4866	1.5335	1.5749	1.6126	1.6477	1.6806
3500	v	0.0160	0.0164	0.0172	0.0183	0.0199	0.0225	0.0307	0.1364	0.1764	0.2066	0.2326	0.2563	0.2784	0.2995	0.3198
	h	77.2	176.0	276.2	379.1	487.6	606.4	779.4	1224.6	1338.2	1422.2	1495.5	1563.3	1629.2	1693.6	1757.2
	s	0.1274	0.2899	0.4312	0.5585	0.6777	0.7973	0.9508	1.3242	1.4112	1.4709	1.5194	1.5618	1.6002	1.6358	1.6691
4000	v	0.0159	0.0164	0.0172	0.0182	0.0198	0.0223	0.0287	0.1052	0.1463	0.1752	0.1994	0.2210	0.2411	0.2601	0.2783
	h	78.5	177.2	277.1	379.8	487.7	606.9	763.0	1174.3	1311.6	1403.6	1481.3	1552.2	1619.8	1685.7	1750.6
	s	0.1271	0.2893	0.4304	0.5573	0.6760	0.7940	0.9343	1.2754	1.3807	1.4461	1.4976	1.5417	1.5812	1.6177	1.6516
5000	v	0.0159	0.0164	0.0171	0.0181	0.0196	0.0219	0.0268	0.0591	0.1038	0.1312	0.1529	0.1718	0.1890	0.2050	0.2203
	h	81.1	179.5	279.1	381.2	488.1	604.6	746.0	1042.9	1252.9	1364.6	1452.1	1529.1	1600.9	1670.0	1737.4
	s	0.1265	0.2881	0.4287	0.5550	0.6726	0.7880	0.9153	1.1593	1.3207	1.4001	1.4562	1.5061	1.5481	1.5863	1.6216
6000	v	0.0159	0.0163	0.0170	0.0180	0.0195	0.0216	0.0256	0.0397	0.0757	0.1020	0.1221	0.1391	0.1544	0.1684	0.1817
	h	83.7	181.7	281.0	382.7	488.6	602.9	736.1	945.1	1188.8	1323.6	1422.3	1505.9	1582.0	1654.2	1724.2
	s	0.1258	0.2870	0.4271	0.5528	0.6693	0.7826	0.9026	1.0176	1.2615	1.3574	1.4229	1.4748	1.5194	1.5593	1.5962
7000	v	0.0158	0.0163	0.0170	0.0180	0.0193	0.0213	0.0248	0.0334	0.0573	0.0816	0.1004	0.1160	0.1298	0.1424	0.1542
	h	86.2	184.4	283.0	384.2	489.3	601.7	729.3	901.8	1124.9	1281.7	1392.2	1482.6	1563.1	1638.6	1711.1
	s	0.1252	0.2859	0.4256	0.5507	0.6663	0.7777	0.8926	1.0350	1.2055	1.3171	1.3904	1.4466	1.4938	1.5355	1.5735

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ANSWERS TO QUESTIONS IN

"Geothermal Energy: Resource and Utilization"

by: V. Thanh Nguyen

1.1 -Hydrothermal Convective Resources

-Geopressured Resources

-Hot Dry Rocks

-Normal Gradients

-Magma Resources

1.2 Only hydrothermal convective resources are currently utilized. Other types such as geopressured resources, hot-dry rocks, normal gradients and magma resources are being explored but are not yet commercially utilized. The description of hydrothermal convective resources is briefly given in section 1.1 of the text.

1.3 From Table 1, world electric generation from geothermal resources in 1978 is 1466.6 Megawatts and non-electric generation in 1975 is 6166 Megawatts. Thus the amount of geothermal energy used is:

For electric generation = $\frac{1466.6}{0.10}$ = 14666 Megawatts

For non-electric applications = $\frac{6166}{0.85}$ = 7254 Megawatts

thus the fraction for non-electric applications is:

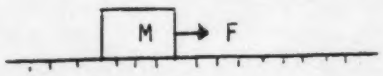
$$\frac{7254}{7254 + 14666} = \boxed{0.331} \quad \text{answer}$$

1.4 Heat available = $\frac{502 \times 1}{0.17}$ = 2952.94 Megawatts

This is equivalent to $2952.94 \times 3.145 = 9287 \times 10^6$ Btu/hr. Amount of steam extracted from the ground is:

$$\frac{9287 \times 10^6 \text{ Btu/hr}}{1100 \text{ Btu/lb}} = \boxed{8.44 \times 10^6 \text{ pounds/hr}}$$

answer

2.1 

$F = Ma$

$$a = \frac{F}{M} = \frac{13 \text{ Newtons}}{10 \text{ kg}} = \boxed{1.3 \text{ m/s}^2}$$

2.2 $P = F \times v$

$= 13 \text{ Newtons} \times 7.5 \text{ m/s} = \boxed{97.50 \text{ watts}}$

2.3 $E = F \times d$

$= 13 \text{ Newtons} \times 1250\text{m} = 16250 \text{ joule} = 16250 \text{ watt-s}$

$$= \frac{16250}{3600000} = \boxed{0.00451 \text{ kwh}}$$

2.4 Assuming that conversion losses are negligible

$$P = E/t \rightarrow t = \frac{E}{P}$$

$$= \frac{16250 \text{ watt-s}}{2000 \text{ watt}} = \boxed{8.125 \text{ seconds}}$$

2.5 (a) Taking relative to melting ice temperature:

$(100^\circ\text{C} - 0^\circ\text{C}) = (T(^\circ\text{F}) - 32^\circ\text{F})/1.8$

$T(^\circ\text{F}) = 100 \times 1.8 + 32 = \boxed{212^\circ\text{F}}$

(b) $T(^\circ\text{K}) = T(^\circ\text{C}) + 273.16$

$= 100 + 273.16 = \boxed{373.16^\circ\text{k}}$

(c) $T(^\circ\text{R}) = 1.8 \times T(^\circ\text{K})$

$= 1.8 \times 373.16 = 671.69^\circ\text{R}$

Note that if $T(^\circ\text{R})$ is calculated as follows:

$T(^\circ\text{R}) = T(^\circ\text{F}) + 459.58 = 212 + 459.58 = 671.58^\circ\text{R}$

from (a)

The difference is due to the fact that melting ice is not exactly at 32°F.

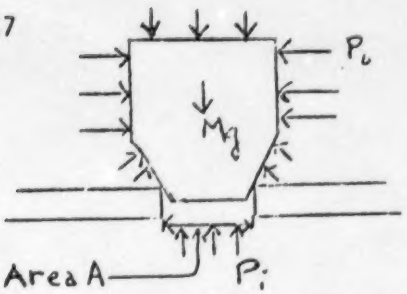
2.6 (a) Since $\Delta T(^\circ K) = \Delta T(^\circ C)$, $\rightarrow$ **1 cal/°K**

(b) 1°F is a smaller interval than 1°C, therefore requires less heat by a factor of 1.8

$$\frac{1}{1.8} = \boxed{0.556 \frac{cal}{^\circ F}}$$

(c) $\Delta T(^\circ R) = \Delta T(^\circ F) \Rightarrow$ **0.556 Cal/°R**

2.7



The highest possible pressure inside the cooker is the pressure which exerts air upward force on the weight that equals the weight plus the force acting on this weight by outside pressure.

Net force due to pressure Po = $P_oA\downarrow$

Weight of the weight = $Mg/g_c\downarrow$, M: mass

g: gravity

g_c: unit conversion

$= 32.174 \frac{lbm\ ft}{lbf\ s^2}$

Force due to inside $P_1 = P_iA\uparrow$

Force balance: $P_oA = P_oA + M \frac{g}{g_c}$

Assuming g has standard value, i.e. 32.174 ft/s^2

$$P_i = P_o + \frac{M\ (lb_f)}{A}$$

$$= 14.6 + \frac{1/8}{\pi\frac{(3/16)^2}{4}}$$

$= 14.6 + 4.53 =$ **19.13 pound (force) per square inch.**

2.8 The system operates between 800°C and 25°C, the Carnot efficiency is

$$y_c = 1 - \frac{273.16 + 25}{273.16 + 800} = 0.722 \text{ or } \boxed{72.2\%}$$

2.9 $\Delta H = \int_{T_1}^{T_2} C_p dT$

$$= \int_{40}^{240} a\,(1 + 10^{-2}T + 10^{-4}T^2)\,dT$$

$$= \int_{40}^{240} a\,dT + \int_{40}^{240} ax10^{-2}T\,dT + \int_{40}^{240} ax10^{-4}T^2\,dT$$

$$= a(240 - 40) + a\frac{10^{-2}}{2}(240^2 - 40^2) + a\frac{10^{-4}}{3}(240^3 - 40^3)$$

$$= 200a + 280a + 458.67\,a = \boxed{938.67a\ \frac{Btu}{lb}}$$

2.10 Heat required in coldest day = 100 rooms x 10^4 $\frac{Btu/hr}{room}$

$= 10^6$ Btu/hr

To provide this heat, the brine must deliver:

$$\frac{10^6\ Btu/hr}{4 \times 10^4\ lb/hr} = 25\ Btu/lb$$

The brine is at 190°F at wellhead. This temperature is below water boiling point at atmospheric pressure. Hence the brine is hot water. For hot water near atmospheric pressure, enthalpy is a function of temperature and not pressure and can be taken as enthalpy of saturated water at the same temperature.

$H_{190°F} - H_{out} = 25$ Btu/lb

$H_{out} = H_{190°F} - 25 = h_{f,\ (at\ 190°F)} - 25$

$= 158.04 - 25 = 133.04\ \frac{Btu}{lb}$,

where the numerical value of h_f is read from the steam table.

The value of 133.04 $\frac{Btu}{lb}$ is between the values for h_f at 160°F and 170°F (see steam table). Interpolation gives:

$$\frac{T_{out} - 160}{170 - 160} = \frac{133.04 - 127.96}{137.97 - 127.96} = 0.507$$

$$T_{out} = 160 + (170 - 160) \times 0.507$$

$$= \boxed{165.07\ ^\circ F}$$

Yes, the process is feasible because the water leaving the hospital is still quite warm (165.07°F).

2.11 $W_{max} = (H - H_o) - T_o (S - So)$

From steam table:

$H = H_{f,\text{at } 190^\circ F} = 158.04$ Btu/lb

$H_o = H_{f,\text{ at } 40^\circ F} = 8.03$ Btu/lb

$S = S_{f,\text{ at } 190^\circ F} = 0.2787$ Btu/(lb°F)

$S_o = S_{f,\text{ at } 40^\circ F} = 0.0162$ Btu/(lb°F)

$T_o = 40 + 459.58 = 499.58^\circ R$

$W_{max} = (158.04 - 8.03) - 499.58\ (0.2787 - 0.0162)$

$= 150.01 - 131.14 = \boxed{18.87\ \frac{Btu}{lb}}$

2.12 $W_{max} = (H - H_o) - T_o(S - S_o)$

(a) $H = H_{g,\ 250^\circ F} = 1164.0$ Btu/lb from steam table

$S = S_{g,\ 250^\circ F} = 1.700$ Btu/(lb°F)

$H_o = H_{f,\text{ at } 80^\circ F} = 48.04$ Btu/lb

$S_o = S_{f,\text{at } 80^\circ F} = 0.0932$ Btu/(lb°F)

$T_o = 80 + 459.58 = 539.58\ ^\circ R$

$W_{max} = (1164 - 48.04) - 539.58\ (1.70 - 0.0932) = \boxed{248.96\ \frac{Btu}{lb}}$

(b) Similarly, $H = H_{f,\text{ at } 250^\circ F}$, $S = S_{f \text{ at } 250^\circ F}$

$$W_{max} = (218.59 - 48.04) - 539.58\ (0.3677 - 0.0932) = \boxed{22.44\ \frac{Btu}{lb}}$$

2.13 The steam is superheated steam.

$H = (1000^{\circ}F,\ 1000\ psia) = 1504.4\ Btu/lb$

$H_o = H_{f,\ 100^{\circ}F} = 68.0\ Btu/lb$

$S(1000^{\circ}F,\ 1000\ psia) = 1.6530\ Btu/(lb^{\circ}F)$

$S_o = S_{f,\ 100^{\circ}F} = 0.1295\ Btu/(lb^{\circ}F)$

$W_{max} = (1504.4 - 68.0) - (100 + 459.58)\ (1.6530 - 0.1295)$

$= \boxed{583.88\ Btu/lb}$

3.1 Geothermal power plants currently in operation are of three types: Dry steam, Flash steam, and Binary Descriptions of these types are presented in section 3.1 in the text.

3.2 $\eta_u = \dfrac{\text{Net Electricity Output}}{W_{max}} = 0.609$

$W_{max} = (H - H_o) - T_o\ (S - S_o)$

$H = H_{f,\ at\ 300^{\circ}F} = 269.7\ Btu/lb$

$H_o = H_{f,\ at\ 80^{\circ}F} = 48.04\ Btu/lb$

$S = S_{f,\ at\ 300^{\circ}F} = 0.4372\ Btu/lb$

$S_o = S_{f,\ at\ 80^{\circ}F} = 0.0932\ Btu\ (lb^{\circ}F)$

$W_{max} = (269.7 - 48.04) - (80 + 459.58)(0.4372 - 0.0932)$

$= 36.04\ Btu/lb$

Net Electricity Output $= 0.609 \times 36.04 = 21.95\ \frac{Btu}{lb}$

We have 1 Megawatt $= 3.145 \times 10^6\ \frac{Btu}{hr}$

or 1 kw = 3145 Btu/hr

Hence Net Electricity Output $= \dfrac{3145\ Btu/hr/kw}{21.95\ Btu/lb} = \boxed{143.3\ \frac{lb/hr}{kw}}$

The value of 133.04 $\frac{Btu}{lb}$ is between the values for h_f at 160°F and 170°F (see steam table). Interpolation gives:

$$\frac{T_{out} - 160}{170 - 160} = \frac{133.04 - 127.96}{137.97 - 127.96} = 0.507$$

$$T_{out} = 160 + (170 - 160) \times 0.507$$

$$= \boxed{165.07\ ^\circ F}$$

Yes, the process is feasible because the water leaving the hospital is still quite warm (165.07°F).

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$S_o = S_{f,\ at\ 40^\circ F} = 0.0162$ Btu/(lb°F)

$T_o = 40 + 459.58 = 499.58^\circ R$

$W_{max} = (158.04 - 8.03) - 499.58\ (0.2787 - 0.0162)$

$= 150.01 - 131.14 = \boxed{18.87\ \frac{Btu}{lb}}$

2.12 $W_{max} = (H - H_o) - T_o(S-S_o)$

(a) $H = H_{g,\ 250^\circ F} = 1164.0$ Btu/lb from steam table

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$H_o = H_{f,\ at\ 80^\circ F} = 48.04$ Btu/lb

$S_o = S_{f,at\ 80^\circ F} = 0.0932$ Btu/(lb°F)

$T_o = 80 + 459.58 = 539.58\ ^\circ R$

$W_{max} = (1164 - 48.04) - 539.58\ (1.70 - 0.0932) = \boxed{248.96\ \frac{Btu}{lb}}$

(b) Similarly, $H = H_{f,\ at\ 250^\circ F}$, $S = S_{f\ at\ 250^\circ F}$

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$S(1000^{\circ}F,\ 1000\ psia) = 1.6530\ Btu/(lb^{\circ}F)$

$S_o = S_{f,\ 100^{\circ}F} = 0.1295\ Btu/(lb^{\circ}F)$

$W_{max} = (1504.4 - 68.0) - (100 + 459.58)\ (1.6530 - 0.1295)$

$= \boxed{583.88\ Btu/lb}$

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Net Electricity Output $= 0.609 \times 36.04 = 21.95\ \frac{Btu}{lb}$

We have 1 Megawatt $= 3.145 \times 10^6\ \frac{Btu}{hr}$

or 1 kw = 3145 Btu/hr

Hence Net Electricity Output $= \dfrac{3145\ Btu/hr/kw}{21.95\ Btu/lb} = \boxed{143.3\ \frac{lb/hr}{kw}}$

The value of 133.04 $\frac{Btu}{lb}$ is between the values for h_f at 160°F and 170°F (see steam table). Interpolation gives:

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$T_o = 80 + 459.58 = 539.58\ ^\circ R$

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(b) Similarly, $H = H_{f,\ at\ 250^\circ F}$, $S = S_{f\ at\ 250^\circ F}$

$$W_{max} = (218.59 - 48.04) - 539.58\ (0.3677 - 0.0932) = \boxed{22.44\ \frac{Btu}{lb}}$$

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$S_o = S_{f,\ 100^{\circ}F} = 0.1295\ Btu/(lb^{\circ}F)$

$W_{max} = (1504.4 - 68.0) - (100 + 459.58)\ (1.6530 - 0.1295)$

$= \boxed{583.88\ Btu/lb}$

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$W_{max} = (269.7 - 48.04) - (80 + 459.58)(0.4372 - 0.0932)$

$= 36.04\ Btu/lb$

Net Electricity Output $= 0.609 \times 36.04 = 21.95\ \frac{Btu}{lb}$

We have 1 Megawatt $= 3.145 \times 10^6\ \frac{Btu}{hr}$

or 1 kw = 3145 Btu/hr

Hence Net Electricity Output $= \dfrac{3145\ Btu/hr/kw}{21.95\ Btu/lb} = \boxed{143.3\ \frac{lb/hr}{kw}}$

The value of 133.04 $\frac{Btu}{lb}$ is between the values for h_f at 160°F and 170°F (see steam table). Interpolation gives:

$$\frac{T_{out} - 160}{170 - 160} = \frac{133.04 - 127.96}{137.97 - 127.96} = 0.507$$

$$T_{out} = 160 + (170 - 160) \times 0.507$$

$$= \boxed{165.07\ ^\circ F}$$

Yes, the process is feasible because the water leaving the hospital is still quite warm (165.07°F).

2.11 $W_{max} = (H - H_o) - T_o (S - So)$

From steam table:

$H = H_{f,at\ 190^\circ F} = 158.04$ Btu/lb

$H_o = H_{f,\ at\ 40^\circ F} = 8.03$ Btu/lb

$S = S_{f,\ at\ 190^\circ F} = 0.2787$ Btu/(lb°F)

$S_o = S_{f,\ at\ 40^\circ F} = 0.0162$ Btu/(lb°F)

$T_o = 40 + 459.58 = 499.58^\circ R$

$W_{max} = (158.04 - 8.03) - 499.58\ (0.2787 - 0.0162)$

$= 150.01 - 131.14 = \boxed{18.87\ \frac{Btu}{lb}}$

2.12 $W_{max} = (H - H_o) - T_o(S-S_o)$

(a) $H = H_{g,\ 250^\circ F} = 1164.0$ Btu/lb from steam table

$S = S_{g,\ 250^\circ F} = 1.700$ Btu/(lb°F)

$H_o = H_{f,\ at\ 80^\circ F} = 48.04$ Btu/lb

$S_o = S_{f,at\ 80^\circ F} = 0.0932$ Btu/(lb°F)

$T_o = 80 + 459.58 = 539.58\ ^\circ R$

$W_{max} = (1164 - 48.04) - 539.58\ (1.70 - 0.0932) = \boxed{248.96\ \frac{Btu}{lb}}$

(b) Similarly, $H = H_{f,\ at\ 250^\circ F}$, $S = S_{f\ at\ 250^\circ F}$

$$W_{max} = (218.59 - 48.04) - 539.58\ (0.3677 - 0.0932) = \boxed{22.44\ \frac{Btu}{lb}}$$

2.13 The steam is superheated steam.

$H = (1000^{\circ}F,\ 1000\ psia) = 1504.4\ Btu/lb$

$H_o = H_{f,\ 100^{\circ}F} = 68.0\ Btu/lb$

$S(1000^{\circ}F,\ 1000\ psia) = 1.6530\ Btu/(lb^{\circ}F)$

$S_o = S_{f,\ 100^{\circ}F} = 0.1295\ Btu/(lb^{\circ}F)$

$W_{max} = (1504.4 - 68.0) - (100 + 459.58)\ (1.6530 - 0.1295)$

$= \boxed{583.88\ Btu/lb}$

3.1 Geothermal power plants currently in operation are of three types: Dry steam, Flash steam, and Binary Descriptions of these types are presented in section 3.1 in the text.

3.2 $\eta_u = \dfrac{\text{Net Electricity Output}}{W_{max}} = 0.609$

$W_{max} = (H - H_o) - T_o\ (S - S_o)$

$H = H_{f,\ at\ 300^{\circ}F} = 269.7\ Btu/lb$

$H_o = H_{f,\ at\ 80^{\circ}F} = 48.04\ Btu/lb$

$S = S_{f,\ at\ 300^{\circ}F} = 0.4372\ Btu/lb$

$S_o = S_{f,\ at\ 80^{\circ}F} = 0.0932\ Btu\ (lb^{\circ}F)$

$W_{max} = (269.7 - 48.04) - (80 + 459.58)(0.4372 - 0.0932)$

$= 36.04\ Btu/lb$

Net Electricity Output $= 0.609 \times 36.04 = 21.95\ \frac{Btu}{lb}$

We have 1 Megawatt $= 3.145 \times 10^6\ \frac{Btu}{hr}$

or 1 kw = 3145 Btu/hr

Hence Net Electricity Output $= \dfrac{3145\ Btu/hr/kw}{21.95\ Btu/lb} = \boxed{143.3\ \frac{lb/hr}{kw}}$

3.3 $\eta_u = \dfrac{H - H_1}{H - H_0} = 0.90$

From data in problem 3.2:

$$H - H_1 = 0.9\ (H-H_0)$$

$$269.7 - H_1 = 0.9(269.7 - 48.04) = 199.49$$

$$H_1 = 269.7 - 199.49 = 70.21 \text{ Btu/lb}$$

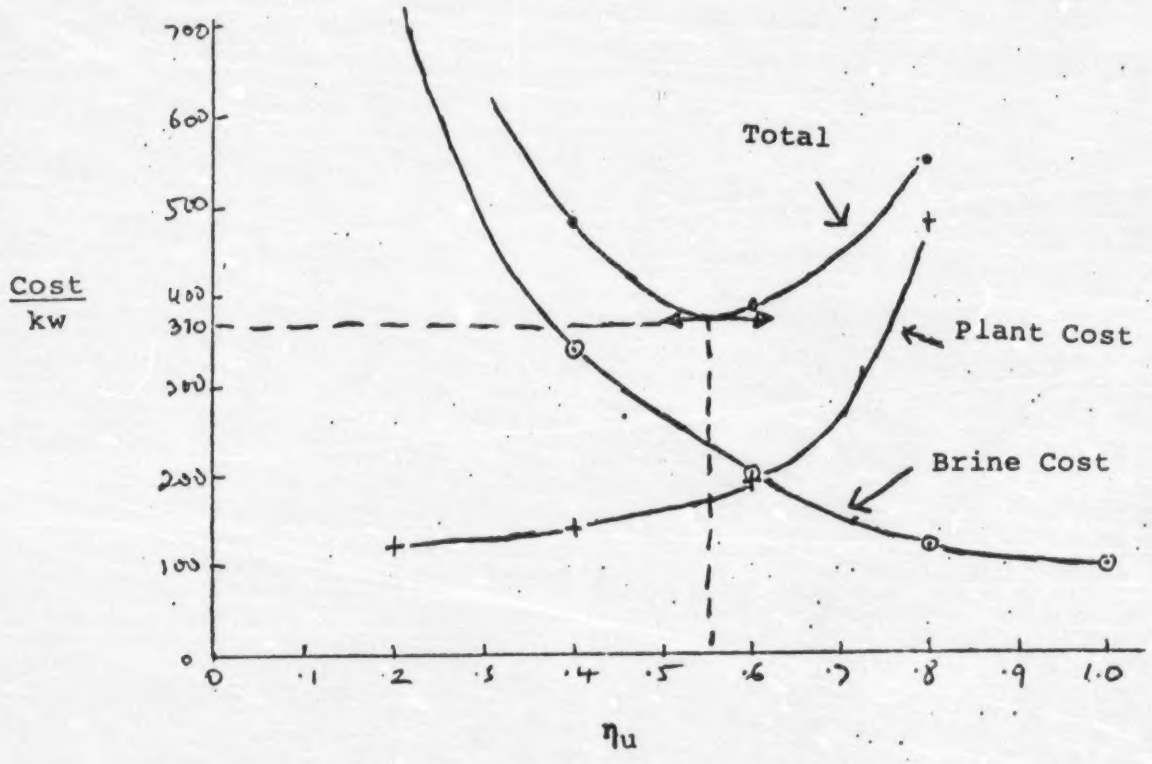
This value falls between η_f values at 100°F and 110°F.

Interpolation:

$$\frac{T_1 - 100}{110 - 100} = \frac{H_1 - 68.00}{77.98 - 68.0} = \frac{70.21 - 68.0}{9.98} = 0.221$$

$$T_1 = 100 + (110 - 100)(0.221) = \boxed{102.21°F}$$

3.4 Plot cost/kw versus



Optimum η_u is 0.55 or 55%

This corresponds to a total cost of $370 per kw